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Climate and weather factors modulating river flows in southern Angola

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ABSTRACT: The large-scale circulation and thermodynamic fields that modulate the flow of the Kavango River in southern Angola during austral summer are studied. According to composite patterns constructed from National Center for Environmental Prediction (NCEP) data, enhanced river flow is associated with an anomalous wave train of upper level winds that emanate from the North Atlantic. Sea-surface temperatures (SST) show a warm-north/cool-south Atlantic dipole condition as the Kavango River rises. Correlations are analysed with respect to the Kavango River flow and a 0 lag value of -0.41 is found for the upper zonal wind over the North Atlantic. Rainfall over the African Sahel region is positively linked with Kavango River flow at 6 month lead time ($r = +0.34$). The work is extended to the event scale and it is found that winds draw tropical moisture over southern Angola in response to an anomalous low-high pair and bifurcated subtropical jet stream. A continental scale sea breeze circulation amplifies the convection during afternoons. Knowledge of run-off into Namibia is critical to the management and planning of water resources in the northern Kalahari savanna. Copyright © 2009 Royal Meteorological Society

KEY WORDS Angola-Namibia river flows; North Atlantic Oscillation; African flood events

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1. Introduction

River run-off is a process by which large-scale water supplies are recharged and maintained for use by nations, cities and communities. In southern Africa significant soil moisture and run-off is limited to the Angolan highlands, Zambezi valley, northern Mozambique and the southeast coast of South Africa (Figure 1a). For a country like Namibia, this poses severe constraints on development, as local replenishment of water resources is infrequent. Almost all of Namibia's water supplies come from the north: the Kunene, Kubango, Kuito, Kavango, Kwando and Zambezi (Figure 1b). With this in mind, our interest is in the factors that modulate the rivers flowing southward from Angola at seasonal and event time-scale.

Tropical Africa is comprised of an extensive region of deep convection and is thus a potential driver of the global circulation; yet our understanding of processes forcing climatic anomalies there is limited. Literature on climate variability arises from regional studies of west, east and southern Africa. Thus the region of Angola represents a notable gap in our understanding of the African climate system. Few studies have attempted to characterize the intra-seasonal (Laing and Fritsch, 1993; Tazalika and Jury, 2008) or interannual rainfall variability (Todd and Washington, 2004; Jury *et al*., 2008) over this region and its links with the global oceans (Jury and Mpeta, 2009). There is evidence of a positive association between tropical African rainfall and Atlantic SSTs (Hirst and Hastenrath, 1983; Jury *et al*., 2000; Rouault *et al*., 2003) and responses to the El Niño Southern Oscillation (ENSO; Camberlin *et al*., 2001; Yeshanew and Jury, 2007) for rivers such as the Congo and Nile (Amarasekara *et al*., 1997).

This paper investigates links between southern Angolan river flow in austral summer and the large-scale atmospheric circulation and ocean thermal patterns. Physical structure and mechanisms are analysed at both seasonal and event scale. A number of questions are addressed: 1. Is climate variability over Angola related to the zonal or meridional circulation of the central Atlantic? 2. Do SST west of Angola affect summer rainfall? and 3. Is the low frequency, time-averaged climate an 'envelope' for high frequency weather events?

2. Data and methods

The study is based on gauge data from the Namibian Hydrological Dept. for river flow at its northern border with Angola (Fig. 1b). These data are gathered upstream from any major cities and may be considered a natural record. Of the time series available, the Kavango River has the largest discharge and most complete record. The monthly river flow data are analysed for seasonal peak and summer (January to April) mean flow (Figure 2a).

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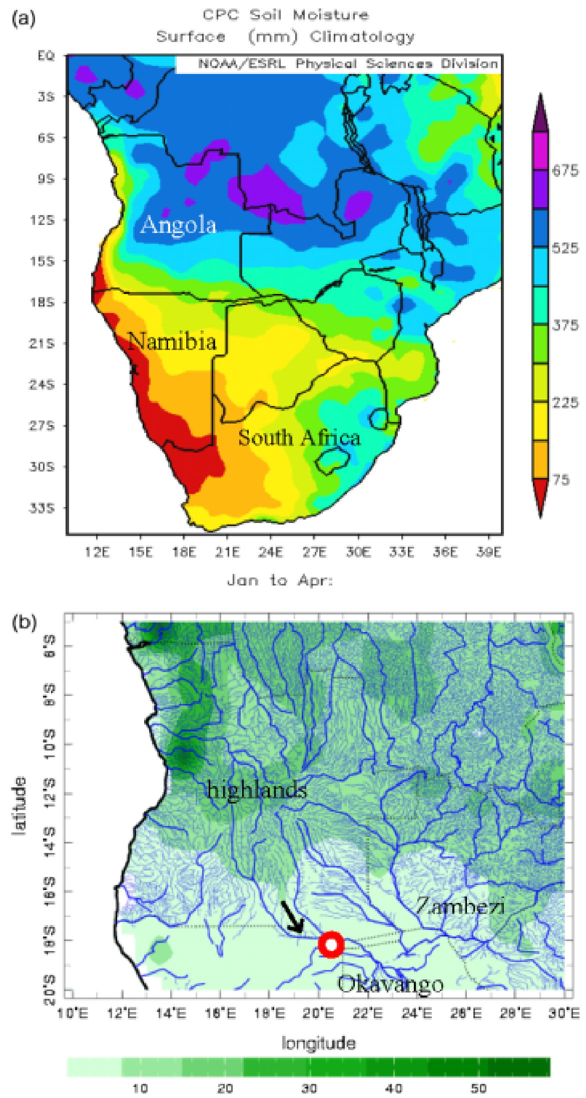

Figure 1. (a) January to April mean soil moisture from CPC reanalysis. (b) Annual mean river run-off (mm/day). Dot indicates the Kavango River gauge at Mukwe, Namibia; arrow illustrates the direction of flow. This figure is available in colour online at www.interscience.wiley.com/ijoc

With the Kavango River catchment extending northwestwards some 1000 km, it is expected that rainfall and climatic elements that govern river flow are influential a month earlier (December to March). The time series of peak and mean flow for the Kavango River is shown in Figure 2b. There is a weak down-trend of 2.5 $m^3\ yr^{-1}$ in the mean record that accounts for 5% of variance. From a ranking of the time series of mean flows, the highest and lowest eight summer seasons were defined. 'Wet' seasons are: 1954, 1962, 1963, 1968, 1969, 1979, 1984, and 2004; 'dry' seasons are: 1967, 1972, 1973, 1974, 1993, 1995, 1996 and 1997.

To assess the factors driving southern Angolan river flow, composite analyses are made with large-scale atmospheric circulation and thermodynamic variables from the National Center for Environmental Prediction (NCEP) reanalysis dataset (Kalnay *et al*., 1996), including Smith and Reynolds (2004) SST data. Todd and Washington (2004) point out that the discontinuities in surface observations and advent of satellite data do not appear to affect the outcome. The composite results are used to isolate key variables for cross-correlation and scatterplot regressions in respect of river flow at various lags. In addition the river flow time series are compared with North Atlantic Oscillation (NAO) index (Jones *et al*., 1997) and northwest Africa (Sahel) rainfall time series.

In the seasonal analysis, the 'dry' field is subtracted from the 'wet' field to form a composite map for interpretation. The composites therefore include 64 months of data. The large-scale climatic elements that are mapped include: sea-surface temperature (SST), winds, vertical motion and the divergent and rotational circulation. At the daily flood scale, similar data are analysed to understand the characteristics of regional circulation anomalies. Gauge and satellite enhanced rainfall over Africa are available from the Global Precipitation Climatology Project (GPCP). The flood composite is based on daily GPCP rainfall for the Kavango catchment area, 12–16 °S,14–20 °E in the period 1998–2005. Following a ranking of cases, the top eight flood days are identified and composite fields are analysed.

3. Results

3.1. Composite seasonal analysis

Before considering the large-scale climate forcing, it is useful to check that wet conditions are evident in the observed fields. For this, the composite wet-minus-dry season rainfall map is evaluated (Figure 3). Summer rainfall is greater as expected over the Angolan highlands, Zambia and southern Tanzania, a zonal axis representing an enhanced inter-tropical convergence zone (ITCZ). Cumulative differences over the season exceed 100 mm in the Kavango catchment and spread into the Zambezi catchment that drains eastward. Drier conditions are found over Botswana, South Africa and areas to the southeast.

SSTs are used in numerical models to predict the climate many months in advance, as the heat fluxes act to shift rain-bearing weather systems. Here the SST fields during and before the composite seasons are analysed. SST differences are negative (cool) in the South Atlantic and south of Africa when the Kavango River is in flood (Figure 4a). Above normal sea temperatures are found in the northwest Atlantic (NW Atlantic). In the preceding season (Figure 4b), SSTs are below normal to the west of Angola extending into the equatorial east Atlantic, and above normal in the North Atlantic. These patterns reflect a N–S dipole with warmer conditions north of the equator and cooler SSTs to the south. The Indian Ocean shows little response in this analysis.

Strongest wind differences at both lower and upper levels (Figure 5) occur in the North Atlantic and are characteristic of negative phase NAO (Marshall *et al*., 2001). Maximum easterly wind differences of 4 to 7 $m\ s^{-1}$ are located between Europe and Canada. Near

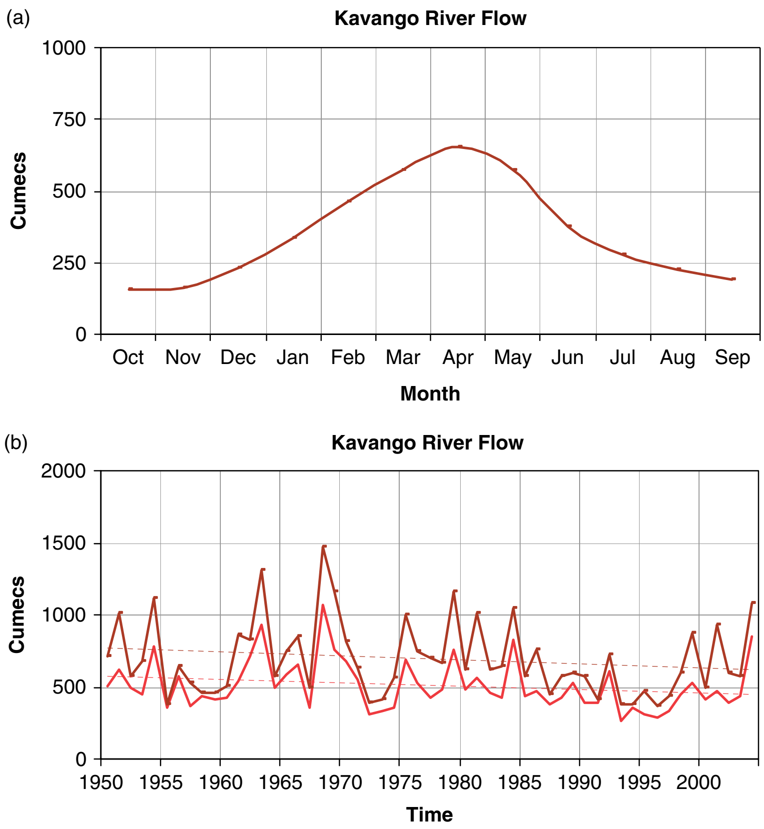

Figure 2. (a) Mean monthly river flow illustrating the annual cycle and April peak. (b) Annual discharge of the Kavango River at Mukwe, Namibia: peak crest (brown) and January to April mean flow (red). Linear trend lines are given. This figure is available in colour online at www.interscience.wiley.com/ijoc

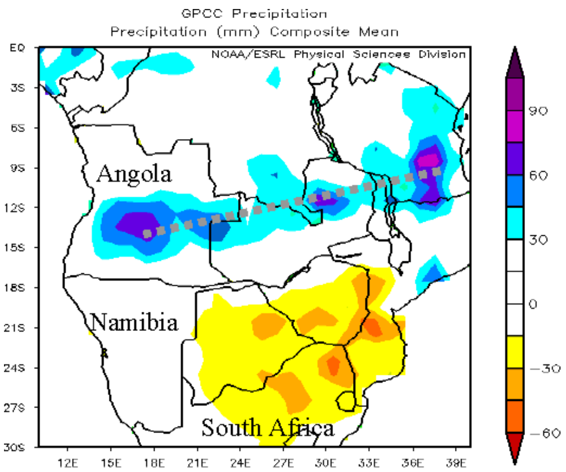

Figure 3. GPCP gauge rainfall for composite wet minus dry summer season. Dashed line highlights ITCZ alignment. This figure is available in colour online at www.interscience.wiley.com/ijoc

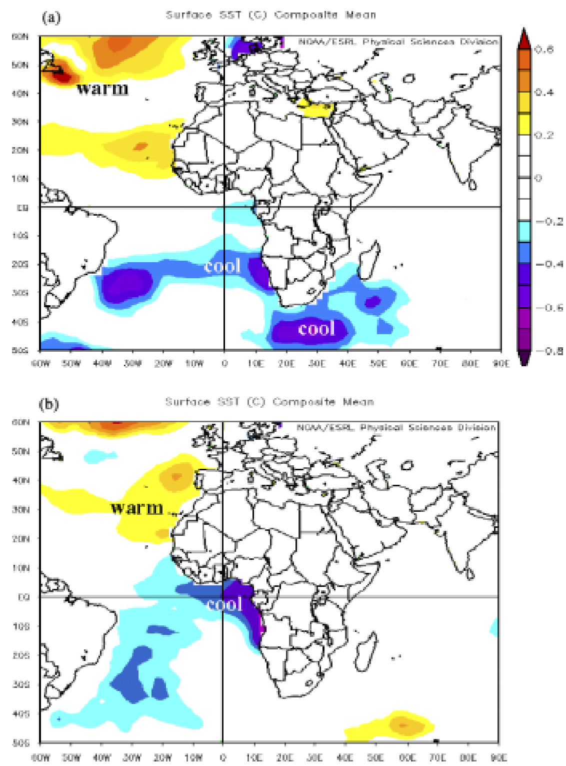

Figure 4. (a) SST for the wet minus dry summer season composite, (b) SST composite 6 months before the rainy season (preceding June–September). Color bar in 0.1 °C intervals. This figure is available in colour online at www.interscience.wiley.com/ijoc

Angola the seasonal differences are also easterly in the lower levels, whilst upper westerly wind differences are found over the central Atlantic. Together these features are consistent with a Walker (zonal overturning) circulation. This signal is distinct from ENSO, and important to river flows that feed the Okavango Delta and its ecosystem.

The upper divergent circulation (Figure 6a) exhibits two centres of action: a broad area of divergence over

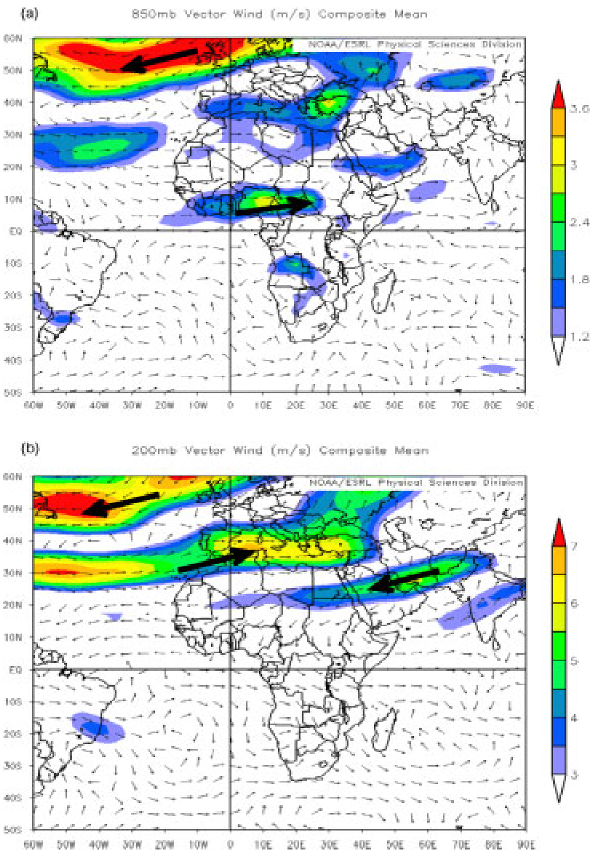

Figure 5. (a) Lower and (b) upper level winds for the wet minus dry summer composite in metre per second. Bold arrows highlight direction of flow in key areas. This figure is available in colour online at www.interscience.wiley.com/ijoc

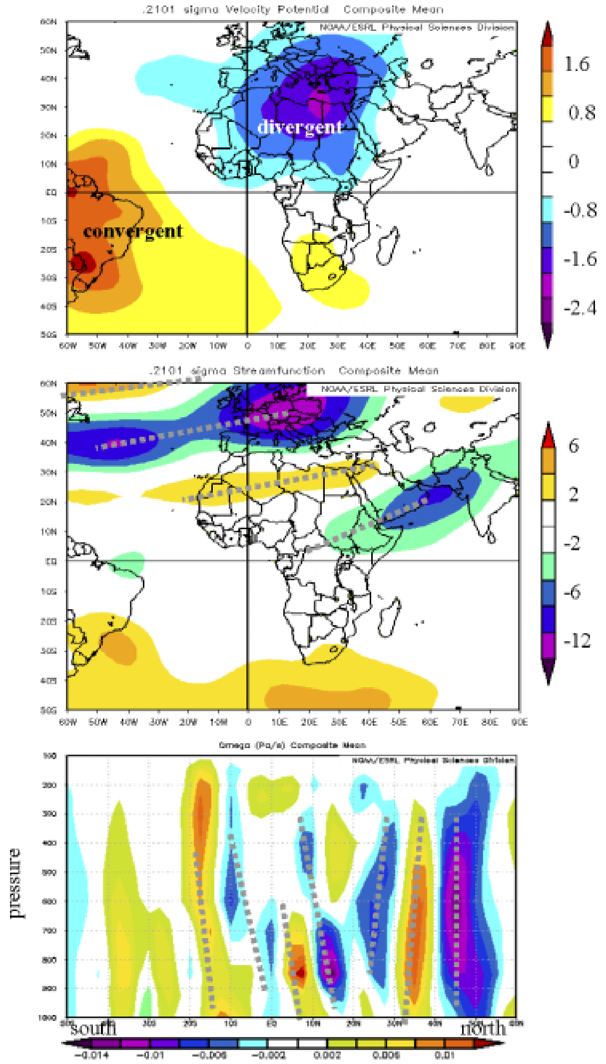

Figure 6. Upper level (0.21 sigma level) velocity potential (a) and stream function (b) and vertical north–south section of omega averaged 10–20 °E (c) for the wet minus dry summer composite. Color bar is $\times 10^6$ m^2 s^{-1} in (a) and (b), and Pa s^{-1} in (c). Grey dashed lines highlight wave-train. This figure is available in colour online at www.interscience.wiley.com/ijoc

North Africa and the Mediterranean, and an opposing area of convergence over South America. Hence gradients of velocity potential across the Atlantic support the Walker Cell there. The upper rotational circulation (Figure 6b) exhibits a pattern consonant with NAO: alternating bands of cyclonic and anti-cyclonic values in the North Atlantic, Mediterranean, Sahara and Congo zones, which affect convection in austral summer as suggested by Rowell and Milford (1993) and Nicholson and Grist (2003). A similar 2000 km wavelength alternation was found by Jury *et al.* (2008) with respect to Congo convection. The vertical section of omega illustrates bands of upward motion interspersed with sinking motion (Fig. 6c).

Compositing rainfall in the preceding June–September period (Figure 7), it was found that the Sahel and India experience wet conditions, whilst southern Europe is dry. This represents yet another indication of NAO influence that appears to propagate southward to Angola with the annual march of the ITCZ from boreal to austral summer.

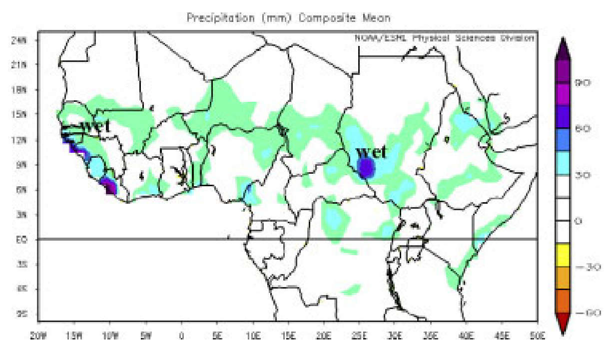

Figure 7. Composite wet minus dry GPCP gauge rainfall in the preceding June to September season. Color bar as in Fig. 2. This figure is available in colour online at www.interscience.wiley.com/ijoc

3.2. Synthesis of seasonal patterns and their statistics

The composite analysis with respect to southern Angolan river flow is characterized by a distinct pattern of winds and related variables over the North Atlantic. These extend throughout the troposphere but peak around 500 hPa. There are multiple bands of alternating sign extending north to south across the Atlantic. This meridional 'wave-train' reflects the NAO climate signal that affects Congo River discharge (Todd and Washington, 2004) and southeast Africa rainfall (McHugh and Rogers, 2001).

The NAO is expressed in tropical Atlantic SSTs and air pressure (Venzke *et al*., 1999; Marshall *et al*., 2001), and relationships with southern Angola river flows can be tested. The Kavango time series exhibits spectral energy at both interannual and decadal periods, consistent with SST fluctuations in the tropical North Atlantic (Melice and Servain, 2003; Andreoli and Kayano, 2004). Todd and Washington (2004) document a significant association of Atlantic SSTs and Congo river flow in the decadal band, but not at the interannual frequency where ENSO is important.

The composite analyses indicate a potential for understanding the climatic mechanisms driving seasonal floods in southern Angola, particularly in respect of the NAO phase. Many of the composite features evolve slowly with time and point to key areas where useful predictors could be drawn. This is done and their statistical significance is evaluated at 0 lag and 6 months preceding. The key variables that are compared with the Kavango River flow include SST in the NW Atlantic (35–55°N, 3060 °W), SST in the tropical east Atlantic (5°N–15 °S, 20 °W–10 °E), 200 hPa zonal wind in the north Atlantic (40–60°N, 20–50 °W), the NAO index and the Sahel rainfall index (as defined by the Climate Diagnostic Center). Table I lists the correlation values and Figure 8 provides scatterplots for leading variables. For ∼50 degrees of freedom, the correlation value should exceed |0.32| to achieve the 98% confidence level. At zero lag, the NAO (−0.36) and upper zonal wind over the North Atlantic (−0.41) achieve statistical significance with respect to the summer season Kavango River flow. These two indices are closely connected with a correlation of +0.80. SST correlations agree with the composite (+N −S dipole), but do not achieve statistical significance with either the river flow or NAO. At least the SST variables exhibit persistence (lag-6 autocorrelation) unlike the atmospheric variables that weaken with time. The Sahel rainfall at 6 month lead time achieves statistical significance with respect to Kavango River flow (+0.34) as indicated by the pattern of velocity potential (*cf* Figure 6a). The Sahel rainfall is low prior to austral summers with low Kavango River flow, but there is greater scatter at the high end (Figure 8c). Other variables are not as reliable in anticipating river flow variations in southern Angola (Table I). The NW Atlantic SST has the highest level of correlation at 6 month lead (−0.14, insignificant), while NAO and upper zonal winds are weak and unstable.

4. Flood event analysis

In this section daily data are used to consider the local scale meteorological scenario surrounding flood events. Satellite-estimated GPCP rainfall is averaged over southern Angola and 3-day totals are ranked. The top eight cases are: 23 January 2003, 21 January 2002, 4 January 2003, 2 February 2002, 16 January 2001, 4 January 2000, 22 January 2000, and 21 January 2001. Composites are constructed by averaging fields for these days; then the historical mean is subtracted to produce 'flood anomaly' maps (Figure 9).

The mid-level vertical motion exhibits a Γ-shape with an axis extending south towards Namibia and east toward Zambia, from the flood centre in southern Angola (Figure 9a). The low-level geopotential height anomaly gives evidence for a subtropical low/mid-latitude high pair that is often referred to as a 'cut-off low'. The jet stream bifurcates south of Africa and a broad ridge is formed. Around the north side of the subtropical low anomalous westerly winds are found in the 850–500 hPa layer that draw moist air towards the southern Angola highlands, according to vertical sections constructed along 10–15 °S in Figure 10.

Thus far, model-interpolated anomalies have been considered; so, to reveal the actual distribution and intensity of rainfall, GPCP data are consulted. In Figure 11, the eight-event composite reveals a maximum over the

Table I. Correlation of key variables with respect to Kavango River January–April flow (Kflow) and peak monthly flow (KflowX) in the period 1951–2000.

	Kflow	KflowX	NAO	NAO − 1	SSTnA	SSTeA	200UA	SSTnA−1	SSTeA − 1	200 UA − 1
KflowX	**0.92**									
NAO	**−0.36**	−0.31								
NAO − 1	−0.04	−0.02	0.12							
SSTnA	0.21	0.23	−0.19	−0.31						
SSTeA	−0.18	−0.19	0.23	0.10	−0.26					
200UA	**−0.41**	**−0.35**	**0.80**	0.10	**−0.39**	**0.34**				
SSTnA−1	−0.14	−0.11	0.29	−0.11	**0.43**	0.09	0.21			
SSTeA−1	−0.08	−0.06	0.13	0.09	−0.08	**0.48**	0.20	0.10		
200 UA − 1	0.08	0.10	0.18	−0.15	0.30	−0.14	0.18	0.15	−0.07	
Sahel − 1	**0.34**	0.25	**−0.34**	−0.17	**0.59**	−0.47	**−0.49**	0.18	−0.22	0.26

NAO, North Atlantic Oscillation; SSTnA, SST in the North Atlantic; SSTeA, SST in the east Atlantic; 200 UA, 200 hPa zonal winds in the North Atlantic; Sahel, tropical African Sahel rainfall.
−1 refers to the preceding June–September season. For 50 degrees of freedom, 98% confidence is reached at $r > |0.32|$ (highlighted bold).

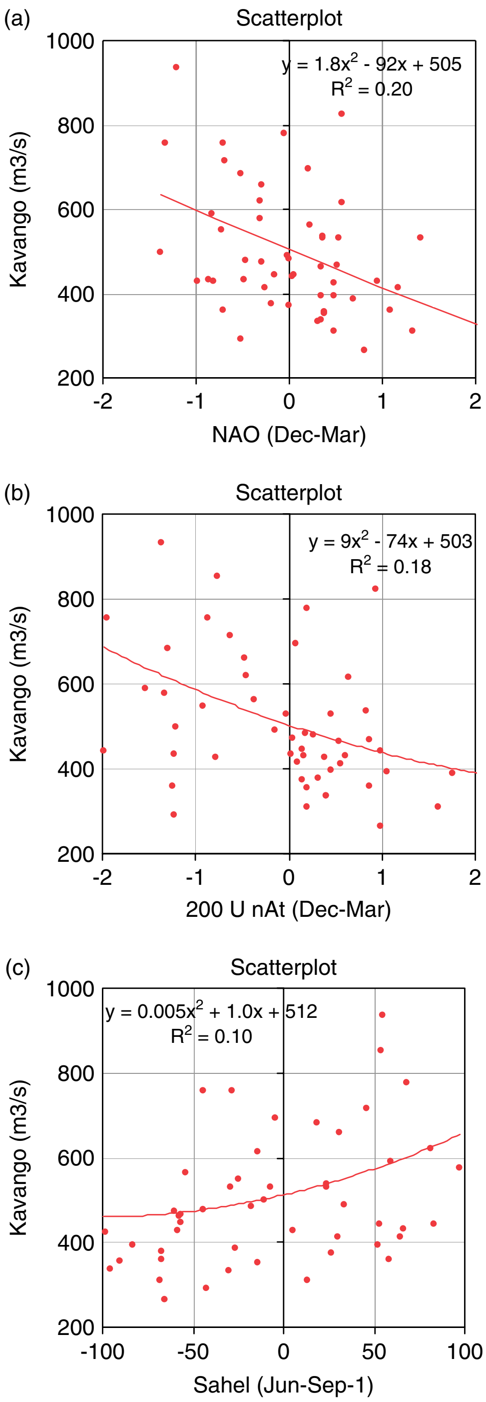

Figure 8. Scatterplot of Kavango River summer flow with respect to departures of: (a) North Atlantic Oscillation, (b) 200 hPa zonal winds over North Atlantic, and (c) Sahel rainfall in preceding June–September season. 2nd order trends and r^2 fit are given. X-axis units for (a) and (b) are standardized departures, units for (c) are millimetres per month. This figure is available in colour online at www.interscience.wiley.com/ijoc

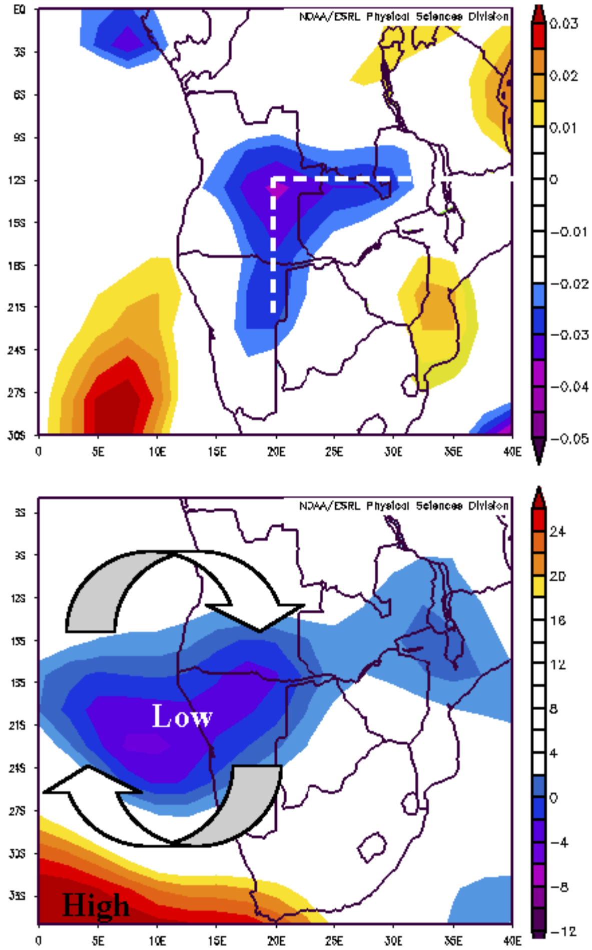

Figure 9. Composite daily anomalies of (a) 500 hPa vertical motion (Pa/s) and (b) 700 hPa geopotential height for eight flood events. Arrows and lines highlight the anomalous circulation. This figure is available in colour online at www.interscience.wiley.com/ijoc

Kavango catchment with an axis extending eastwards into the Zambezi Valley. The 3-day cumulative rainfall exceeds 50 mm over an area 200 × 500 km. If run-off is assumed to be 20%, a total of over 1 B m^3 is available for river discharge southeastwards towards Namibia and Botswana.

The climate and weather factors that conspire to induce flood events are likely to exhibit diurnal amplitude. Therefore composites were made for the 8 flood days by subtracting 0200 LST fields from 1400 LST fields. The results are provided in Figure 12. The surface temperatures show a warm tongue >8 °C extending northwards between 100 and 300 km inland from the west coast according to NCEP reanalysis. The thermal gradients activate a large-scale sea breeze, indicated by southwesterly wind vector differences up to 5 m s^{-1} across Namibia, and vertical uplift is much enhanced during the afternoon over southern Angola. Hence floods triggered by a low–high pair at the weather scale, are amplified by a diurnal sea breeze circulation.

5. Conclusions

Our understanding of climate–weather interactions over tropical Africa is growing. Here links between southern Angolan river flow and the large-scale circulation of the North Atlantic in austral summer are evident at the seasonal time-scale. Wet years are characterized by

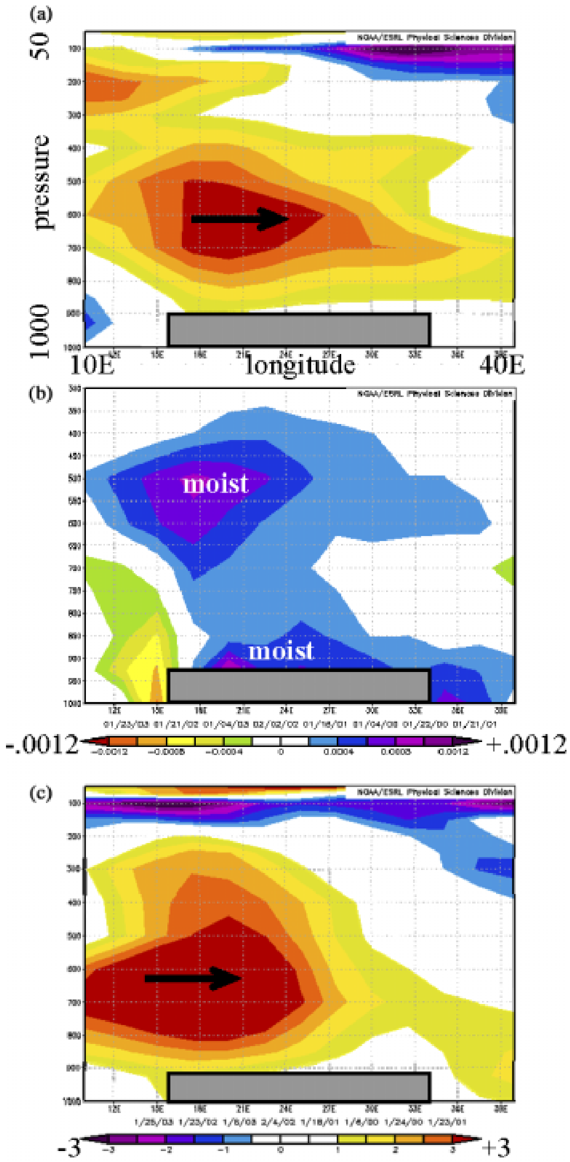

Figure 10. Composite vertical sections of zonal wind anomaly day −2 (a) and day +2 (c), and specific humidity anomaly on day 0 (b), averaged 10–15 °S from 10–40 °E. Pressure (y-axis) is 1000–50 hPa for winds, and 1000–300 hPa for humidity. The highlands are represented by shading. This figure is available in colour online at www.interscience.wiley.com/ijoc

an anomalous meridional wave-train of upper winds, vertical motion and rotational shear (streamfunction), which extends from the NW Atlantic towards southern Africa. While the Atlantic Walker Cell and ENSO have a minor impact on the hydrology of southern Angola, the Atlantic SST dipole and NAO-related wave train are more influential in agreement with the study by Todd and Washington (2004) for the Congo River discharge. Composite observations indicate that the meridional wave-train contributes to alternating zones of high and low rainfall (Melice and Servain, 2003; Andreoli and Kayano, 2004). The daily flood event analysis sought to establish the weather signals embedded within the season. Composite results reveal a low–high geopotential pattern that induces tropical westerlies and mid-latitude easterlies,

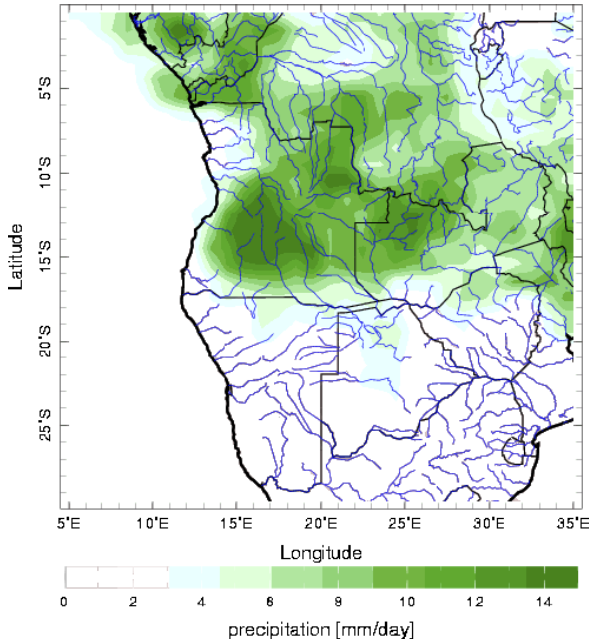

Figure 11. Composite GPCP satellite rainfall for the top eight flood events. This figure is available in colour online at www.interscience.wiley.com/ijoc

thus producing cyclonic vorticity, moisture convergence and uplift. A continental scale sea breeze enhances the convection during afternoon. Although some useful signals at both climate and weather scales have been identified, the explained variance is rather limited. The composites are based on a generous sample size, but extremes may still dictate the relationships.

The Kavango River is a main source of water to Southern Angola and northern Namibia, and together with the Kuito River, feeds the Okavango Delta in northern Botswana – a major ecosystem, animal habitat and international tourist attraction accounting for ~$2 B in annual revenue. Its flows are declining at 2.5 m^3 per year, without any apparent increase in human off-take (eg. irrigation or dams). This decline appears to be related to a regional response to global warming (Jury and Whitehall, 2009). The predictability of water resources linked with meridional modes will be lower than those modulated by zonal modes and their slow moving global waves. Indeed, the only 6 month lead predictor of significant value found here is rainfall over the African Sahel. Hence there is a need for further research to understand the relationship between the large-scale flow and associated wind shear, and the local scale thermodynamic energy sources that contribute to flood and drought events over tropical Africa.

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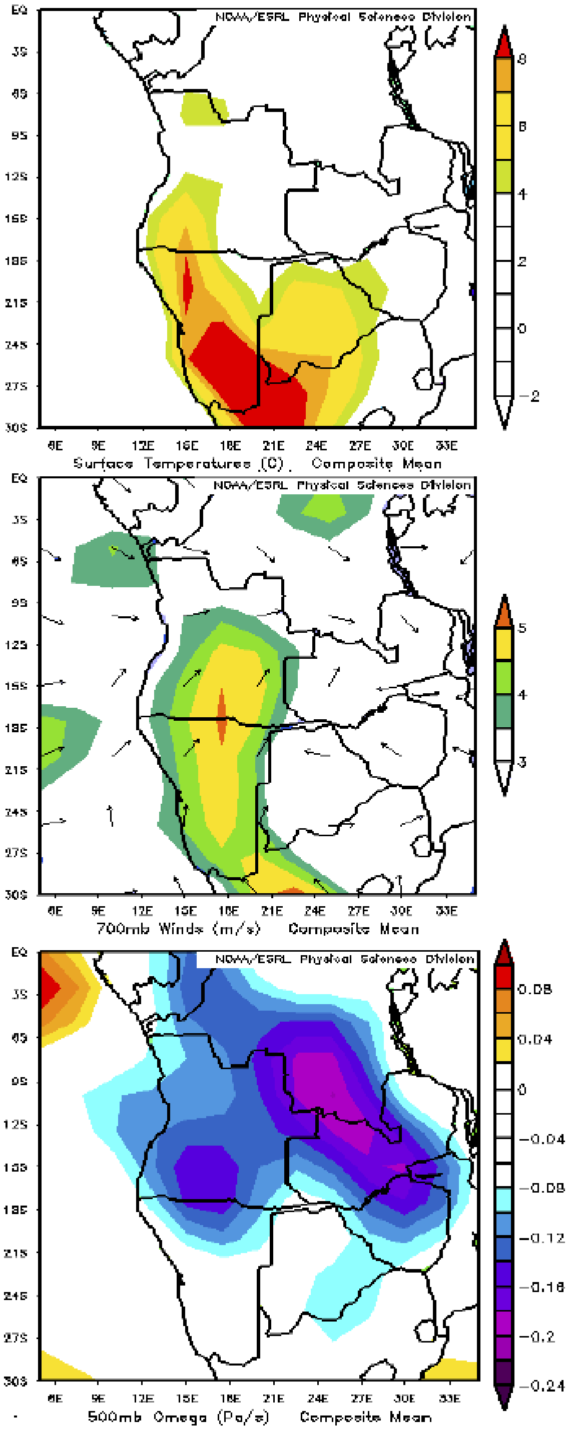

Figure 12. Composite diurnal amplitude maps: 1400 LST minus 0200 LST for the 8 flood days: (a) 2 m air temperature (°C), (b) 700 hPa winds (m s^{-1}), and (c) 500 hPa vertical motion (Pa s^{-1}). This figure is available in colour online at www.interscience.wiley.com/ijoc

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